F-15 DIGITAL ELECTRONIC ENGINE CONTROL SYSTEM DESCRIPTION

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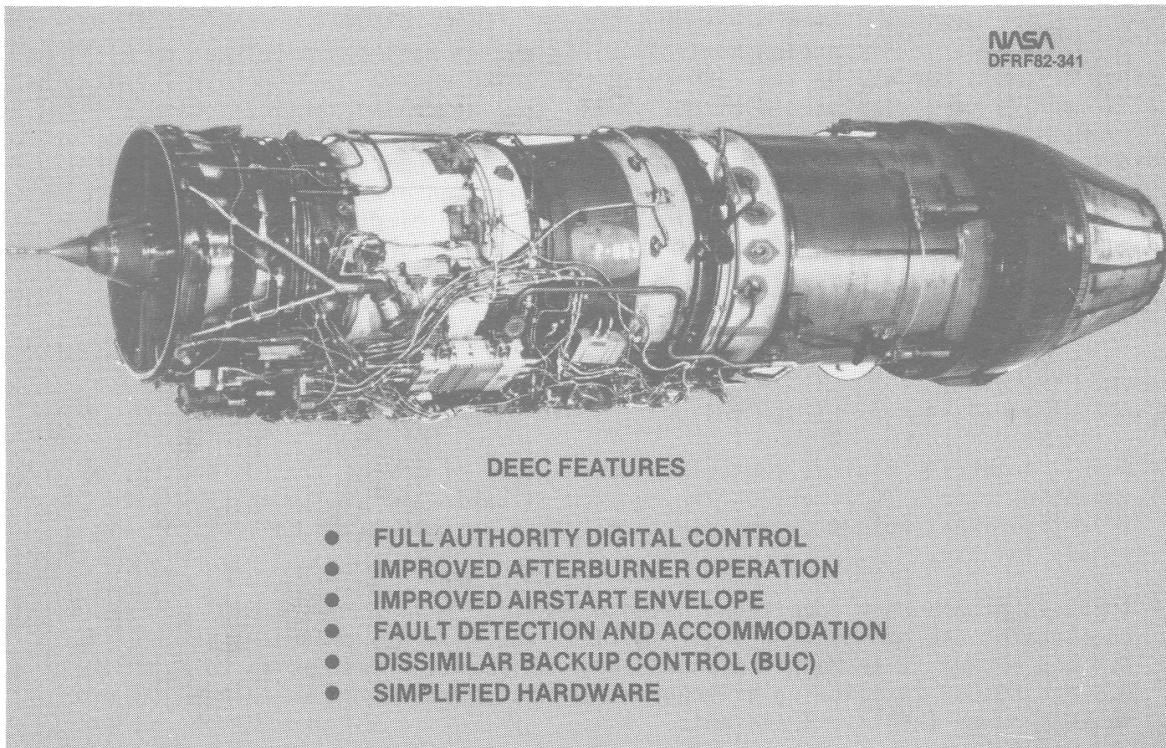Edwards, California

SUMMARY

A digital electronic engine control (DEEC) system has been developed by Pratt and Whitney Aircraft for use on the F100-PW-100 turbofan engine. This control system has full authority control, capable of moving all the controlled variables over their full ranges. The digital computational electronics and fault detection and accommodation logic maintains safe engine operation. A hydromechanical backup control (BUC) is an integral part of the fuel metering unit and provides gas generator control at a reduced performance level in the event of an electronics failure. This paper will describe the DEEC features, hardware, and major logic diagrams.

FEATURES

The DEEC control system has the following features:

- A full authority digital control system capable of moving all the controlled variables over a full range. The control is basically single channel with selective input/output redundancy to maintain gas generator control for any single failure.

- Improved afterburner operation in the upper left hand corner (ULHC) of the flight envelope by use of software logic to limit operation to segment 1 at about Mach 0.4 and 40,000 ft to Mach 1.0 and 50,000 ft; and at altitudes up to about Mach 0.9 and 20,000 ft allowing afterburner initiation to occur at idle on idle-to-maximum power throttle transients.

- Fault detection and accommodation by selective input and output redundancy and parameter synthesis to maintain gas generator control with any single failure.

- Dissimilar BUC, an integral part of the gas generator fuel metering valve unit. The BUC maintains hydromechanical control of the gas generator at a reduced performance level.

- Simplified hardware by reduction of the number of components and quick access to 15-line replaceable units (LRUs) which do not require calibration.

- A fan inlet static pressure (PS2) probe extending about 18 inches in front of the engine inlet.

- A computer that is engine mounted on shock isolators and fuel cooled.

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DEEC FEATURES

- **FULL AUTHORITY DIGITAL CONTROL**
- **IMPROVED AFTERBURNER OPERATION**
- **IMPROVED AIRSTART ENVELOPE**
- **FAULT DETECTION AND ACCOMMODATION**
- **DISSIMILAR BACKUP CONTROL (BUC)**
- **SIMPLIFIED HARDWARE**

The F100-PW-100 engine is a low-bypass ratio (0.8), twin-spool, afterburning turbofan. The three-stage fan is driven by a two-stage, low-pressure turbine. The 10-stage high pressure compressor is driven by a two-stage turbine. The engine incorporates compressor inlet variable vanes (CIVVs) and rear compressor variable vanes (RCVVs) to achieve high performance over a wide range of power settings; a compressor bleed is used only for starting. Continuously variable thrust augmentation is provided by a mixed-flow afterburner, which is exhausted through a variable-area convergent-divergent nozzle.

The augmentor incorporates five spray ring (S/R) segments which come on sequentially. Segments 1, 2, and 4 are located in the core stream, and segments 3 and 5 are located in the fan duct stream. The augmentor is equipped with dual-augmentor ignitors, whereas the standard F100 engine has only one. It also has a ducted core flameholder, which ducts a small amount of hot core flow to the flameholders located in the fan duct stream. The standard F100 engine flameholder does not duct any core air to the fan duct stream. The engine was also equipped with a static pressure probe on the engine hub which is not on the standard F100 engine.

The F100 engine used for the DEEC evaluation was Serial Number 680063. It had been rebuilt from an earlier F100(2) engine to a zero-time F100(3) configuration with the DEEC system before the DEEC flights. The engine had accumulated 9.8 hr of sea level testing and 45.4 hr at an altitude facility before the first DEEC flights.
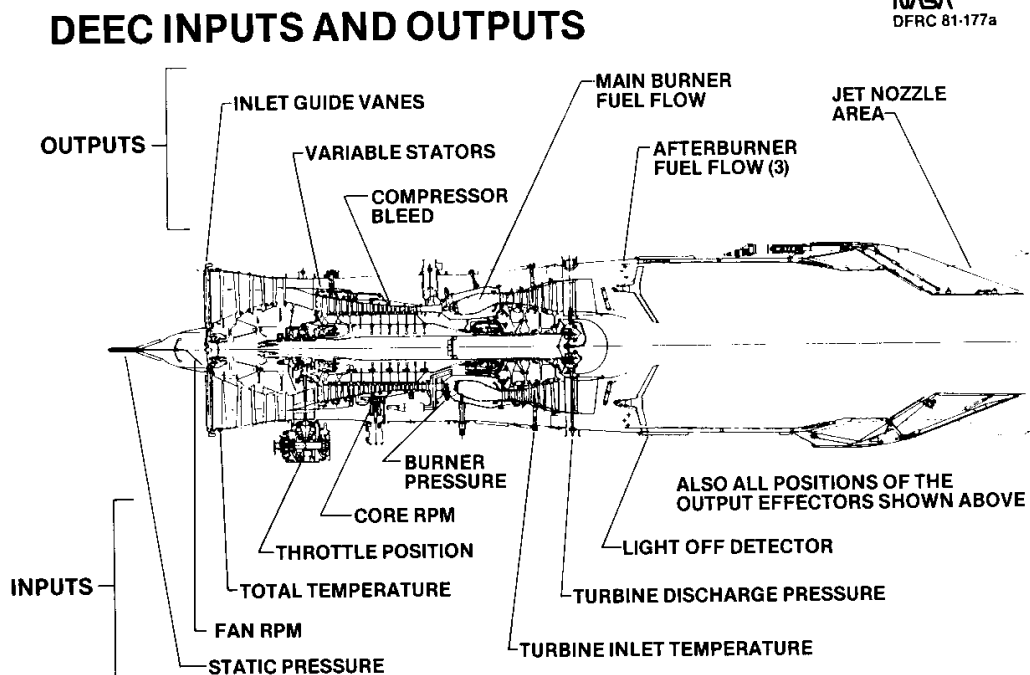
F100 DEEC Test Engine

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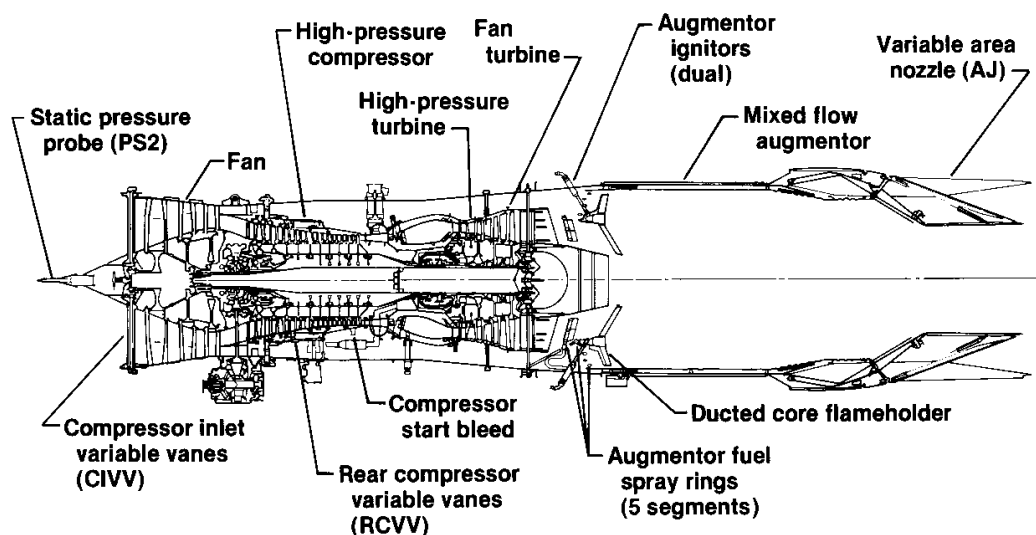
INPUTS AND OUTPUTS

Shown on the upper part of this figure are the controlled variables: compressor inlet variable guide vanes (CIVVs), rear compressor variable stators (RCVVs), start bleeds, main burner gas generator fuel flow (WFGG), afterburner fuel flow in the core (WFAC) and in the duct (WFAD), the sequencing valve position (SVP), and the jet nozzle (AJ).
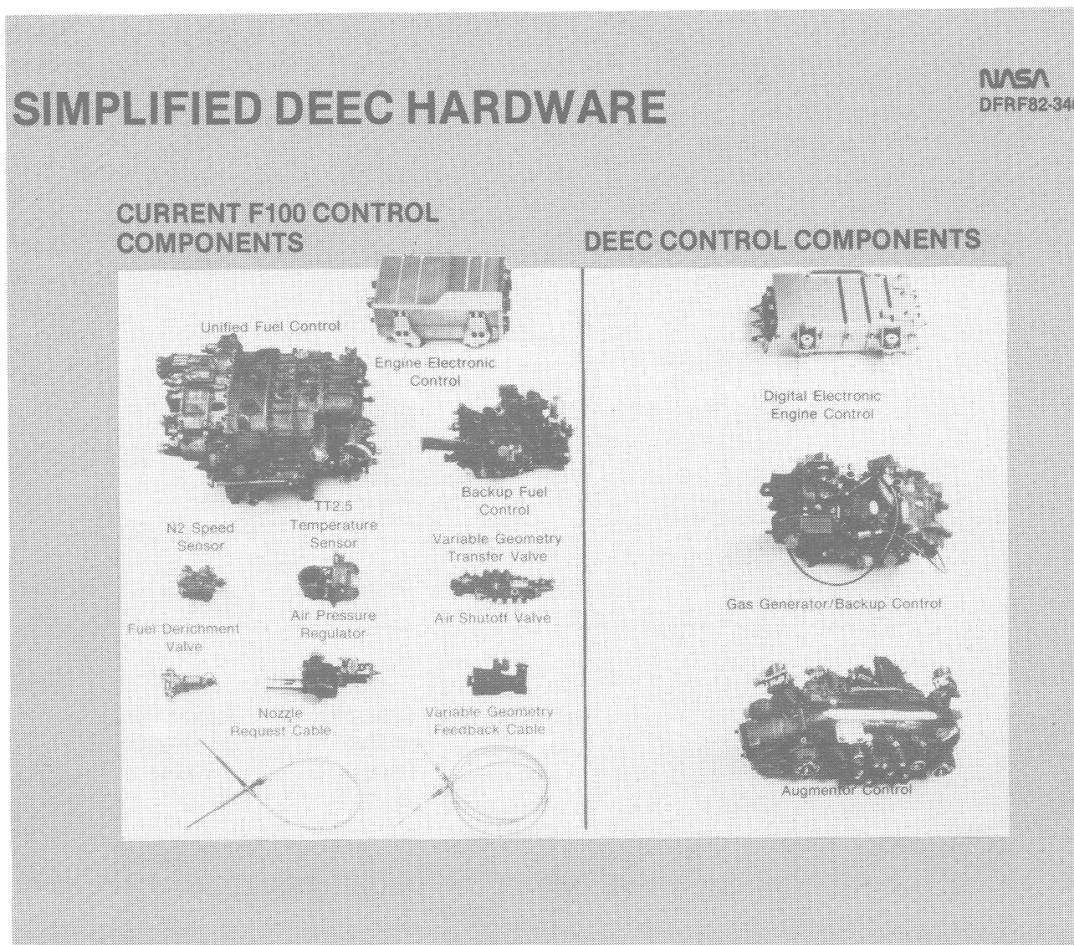
The lower portion of the figure shows the input sensors to the DEEC: engine station 2 fan inlet static pressure (PS2), fan rotor speed (N1), core rotor speed (N2), power lever angle (PLA), engine station 2 fan inlet total temperature (TT2), main burner pressure (PB), fan turbine inlet temperature (FTIT), turbine discharge total pressure (PT6M), ultraviolet light off detector (LOD), and all resolver feedbacks. The DEEC schedules WFGG, RCVV, CIVV, start bleeds, WFAC, WFAD, SVP, and AJ as functions of PLA, PS2, PB, PT6M, N1, N2, TT2, and FTIT.

DEEC INPUTS AND OUTPUTS

OUTPUTS
- INLET GUIDE VANES
- VARIABLE STATORS
- COMPRESSOR BLEED
- MAIN BURNER FUEL FLOW
- AFTERBURNER FUEL FLOW (3)
- JET NOZZLE AREA

INPUTS
- BURNER PRESSURE
- CORE RPM
- THROTTLE POSITION
- TOTAL TEMPERATURE
- FAN RPM
- STATIC PRESSURE
- LIGHT OFF DETECTOR
- TURBINE DISCHARGE PRESSURE
- TURBINE INLET TEMPERATURE

ALSO ALL POSITIONS OF THE OUTPUT EFFECTORS SHOWN ABOVE

SIMPLIFIED HARDWARE

Shown on the left side of this figure are the 11 control system components currently used on the production F100 engine in the F-16 airplane. Engine control is provided by the hydromechanical unified fuel control utilizing an engine electronic control to supervise or trim the hydromechanical control system. Also shown on the left side are various sensors, valves, and feedback cables of a current F100 control system. This control system represents the first operational use of a digital electronic computer on a high performance turbofan engine.

The DEEC control system components, shown on the right side of the figure, illustrate the reduced number, as well as the simplified DEEC hardware. The three major components of the DEEC control system are the DEEC computer, gas generator fuel metering valves and integral backup control, and the augmentor fuel metering valves unit.

SIMPLIFIED DEEC HARDWARE

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CURRENT F100 CONTROL COMPONENTS

DEEC CONTROL COMPONENTS

Unified Fuel Control

Engine Electronic Control

Backup Fuel Control

N2 Speed Sensor

TT2.5 Temperature Sensor

Variable Geometry Transfer Valve

Fuel Derichment Valve

Air Pressure Regulator

Air Shutoff Valve

Nozzle Request Cable

Variable Geometry Feedback Cable

Digital Electronic Engine Control
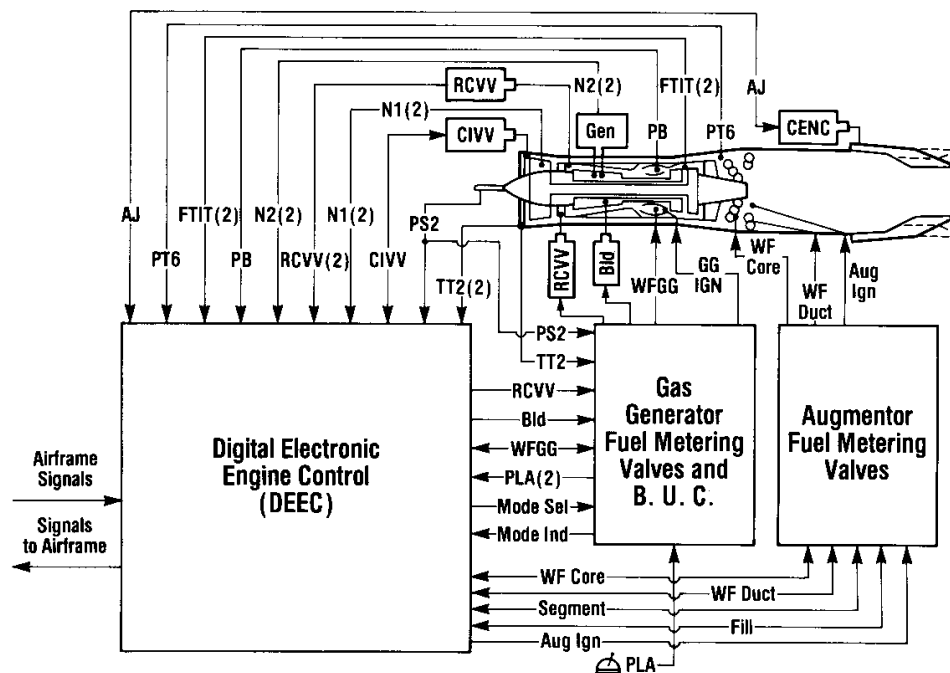
Gas Generator/Backup Control

Augmentor Control

The DEEC system is functionally illustrated below. The three major components of the DEEC control system are the: DEEC computer, gas generator and integral BUC fuel metering valve unit, and the augmentor fuel metering valve unit. Note the shared information between the electronics and the metering valve units.

The DEEC computer receives inputs from the airframe through throttle position (PLA) and Mach number (M), and from the engine through pressure sensors (PS2, PB, PT6M), temperature sensors (TT2, FTIT), and rotor speed sensors (N1, N2). It also receives feedbacks from the controlled variables through position feedback transducers indicating variable vane (CIVV, RCVV) positions, metering valve positions for gas generator fuel flow (WFGG), augmentor core and duct fuel flow (WF), segment sequence valve position, and exhaust nozzle position (AJ). Dual sensors and position transducers are used as shown to achieve redundancy in key parameters as indicated by the (2).

The input information is processed by the DEEC computer to schedule the variable vanes (CIVV, RCVV), to position the compressor start bleeds, to control gas generator and augmentor fuel flows, to position the augmentor segment-sequence valve, and to control exhaust nozzle (CENC) area. Redundant coils are present in the torque motor drivers for all of the actuators.

DEEC Control System

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GAS GENERATOR AND BUC METERING VALVE UNIT

The next figure is a photograph of the gas generator fuel metering valve unit, including the integral backup control (BUC). The digital control uses torque motors to actuate the variables, such as the RCVV and gas generator fuel metering valve torque motors shown at the lower left. The torque motors have dual-wound coils; either coil can control the servovalve. At the lower right is the metering valve resolver feedback and the PLA resolver is illustrated at the upper right. All resolvers in the unit are dual for position feedback redundancy.

If the digital control system experiences a failure that requires a transfer to the backup control, a transfer valve translates to permit the hydromechanical control to schedule the gas generator metering valve and RCVV position. The BUC and electronic control components are functionally integrated to minimize the weight and volume. The BUC is described in Paper 9.

Gas Generator Fuel Metering Valve Unit

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PLA resolver

Gas generator fuel metering valve resolver

Gas generator fuel metering valve torque motor

RCVV torque motor
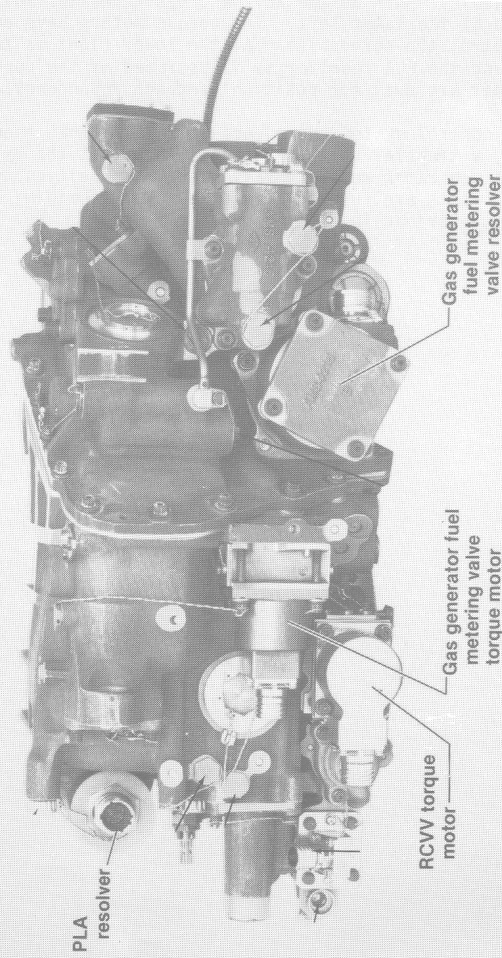
AUGMENTOR FUEL METERING VALVE UNIT

The photograph below shows the augmentor metering valve unit. This unit combines fuel metering, manifold quickfill, and a fuel distribution system into a single unit controlled by signals from the DEEC. Again note the metering valve and segment sequencing valve torque motors and resolver locations.

Augmentor Fuel Metering Valve Unit

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Segment sequencing valve torque motor

PFMO

Duct metering valve torque motor

Segment sequencing valve resolver

Core metering valve torque motor

Duct metering valve resolver

Core metering valve resolver
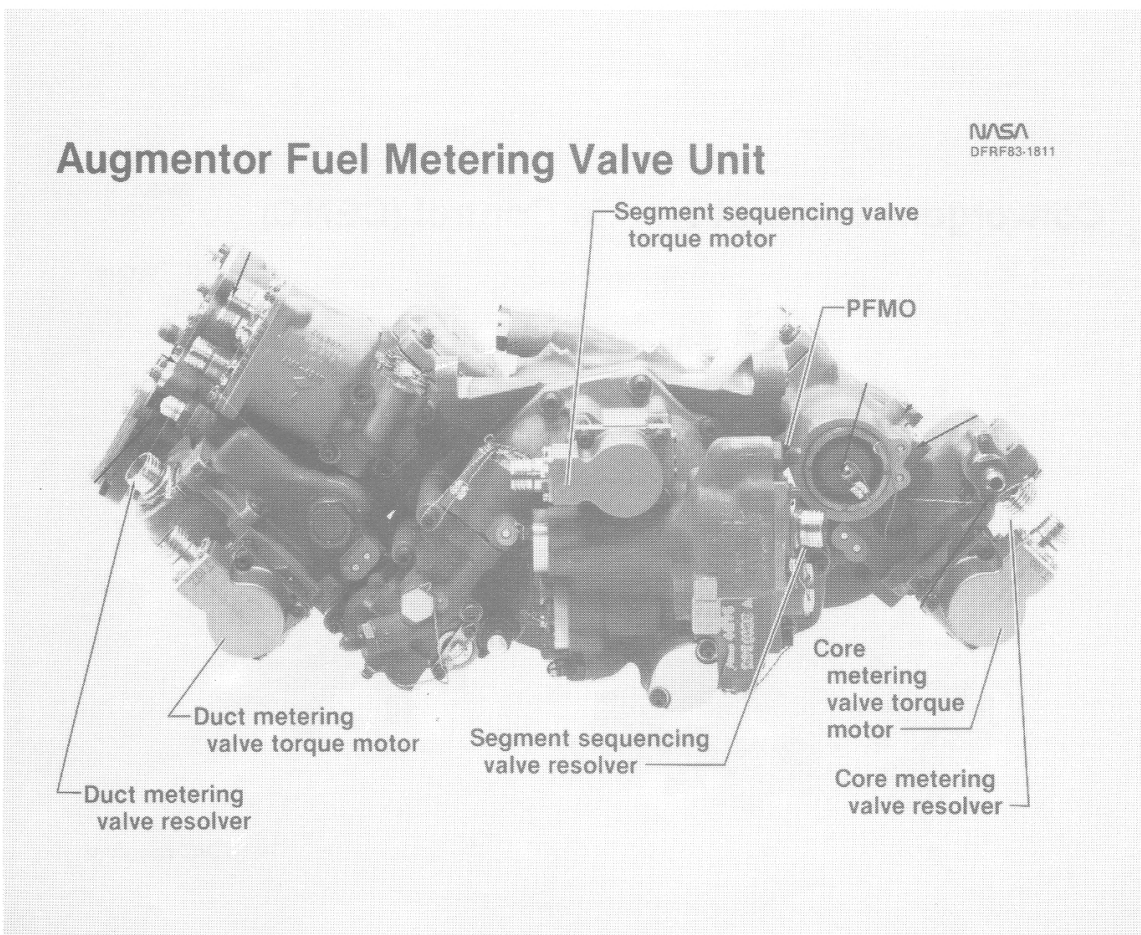
CONVERGENT EXHAUST NOZZLE CONTROL

The convergent exhaust nozzle control (CENC) positions the jet nozzle in response to commands from the DEEC. The CENC consists of a reversible air motor, a bidirectional control valve, a four-way torque motor, and a resolver. The air motor is driven by compressor bleed air. The torque motor is biased by a null voltage to provide for a fail-safe failure mode in the closed-nozzle direction.

Convergent Exhaust Nozzle Control (CENC)

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Air motor

CENC torque motor

CENC resolver
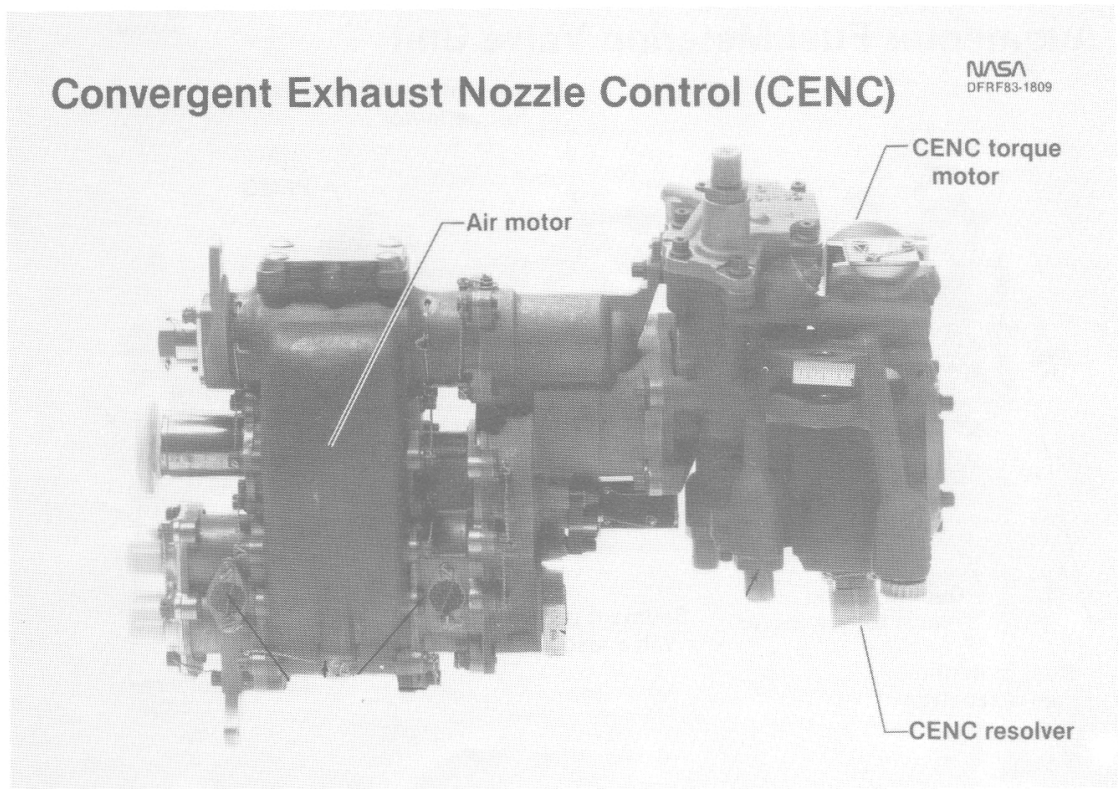
CIVV ACTUATOR

The torque motor mounted on the actuator modulates the fuel pressure to position the compressor inlet variable vanes (CIVVs). The torque motor is controlled by a signal from the DEEC. The resolver provides position feedback. Both the torque motor and resolver are illustrated at the top of the actuator.
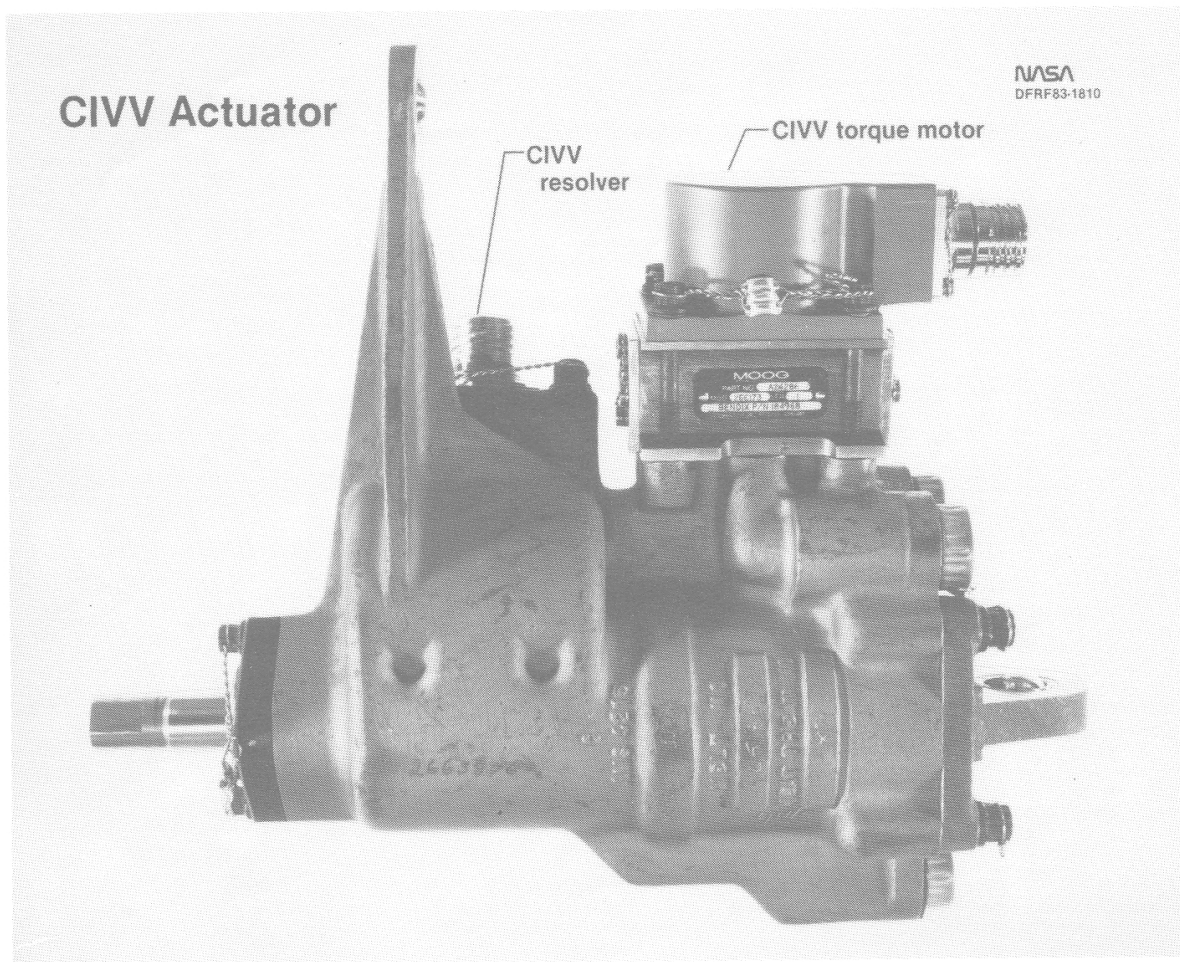
DEEC ON F100 ENGINE

The DEEC computer is engine mounted as shown in the next figure. The housing is split-cast aluminum and is mounted on shock isolators. Moving in a clockwise direction around the figure are the power supplies and aircraft interface, output interfaces, pressure sensors PS2, PB, and PT6M, vibrating cylinder transducers that are temperature compensated, input interface, and the computer processor and memory. The entire unit is fuel-cooled.

DEEC ON F-100 ENGINE

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DEEC

HOUSING

POWER SUPPLY & AIRCRAFT INTERFACE

OUTPUT INTERFACES

PRESSURE SENSORS

INPUT INTERFACES

COMPUTER PROCESSOR AND MEMORY
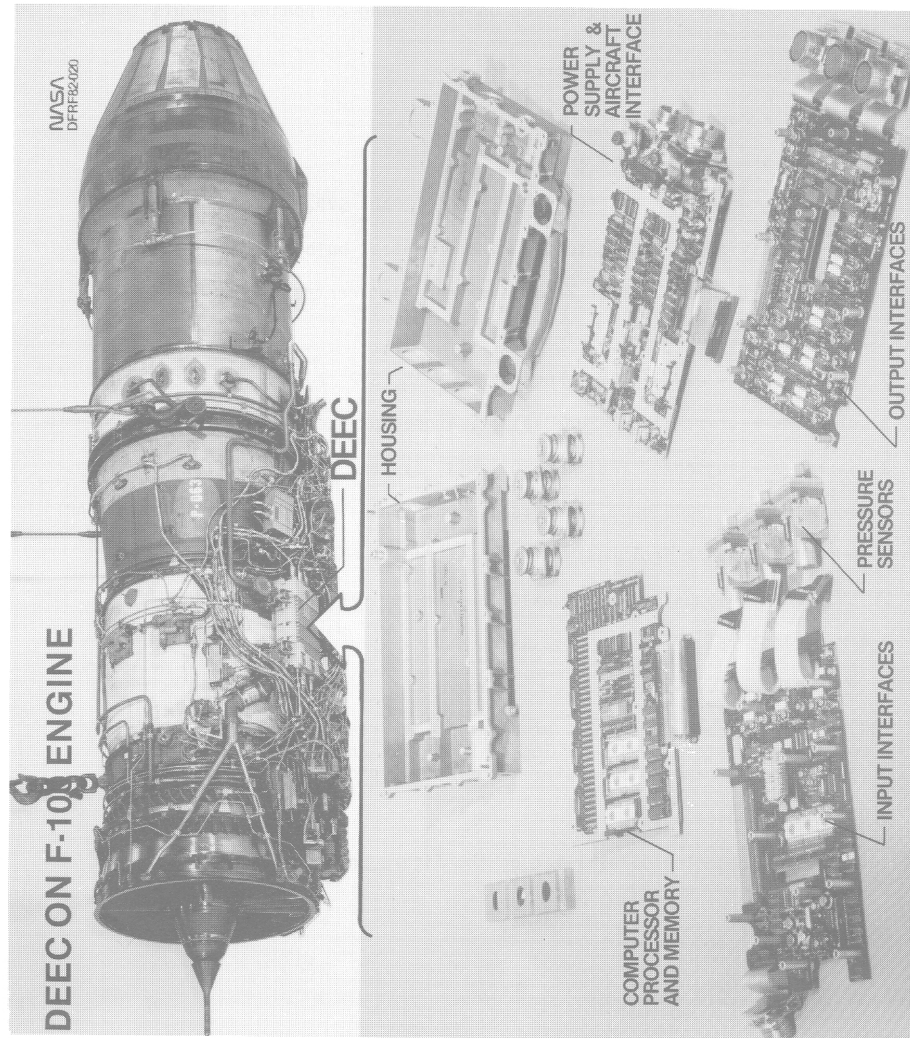
DEEC COMPUTER

The DEEC computer is a fuel-cooled unit weighing 28 pounds. Inputs to the unit are:

4 temperature - TT2 a and b, FTIT a and b;

3 pressure - PS2, PB, PT6M;

4 speeds - N1 a and b, N2 a and b;

11 positions - PLA, RCVV, CIVV, WFGG, WFAC, WFAD, SVP, AJ;

1 LOD - ultraviolet flame detector with self-test bulb; and

1 digital word - Mach number from airframe inlet controller.

Outputs for the DEEC computer are:

7 servodrivers - CIVV, RCVV, WFGG, WFAD, WFAC, SVP, AJ;

3 solenoids - start bleed, mode select, augmentor fuel pump;

3 discretes - augmentor fault, DEEC fault, system fault; and

1 digital word - 9600 baud, universal asynchronous receiver transmitter (UART).

The DEEC unit processor includes:

11 chips - complementary metal oxide substrate (CMOS) construction;

3.4-MHz clock rate - quartz crystal;

1.2-microsecond cycle time;

14K memory - 16-bit words, 10K of programmable read-only
    memory transistor-transistor logic (PROM-TTL) and 512
    random access memory transistor-transistor logic (RAM-TTL); and

110 watts of power used.

Logic of the DEEC is also illustrated on the figure on the next page.

DEEC Computer

Input
- Temperature   4
- Pressures   3
- Speeds   4
- Positions   11
- LOD   1
- Digital   1

Processor
- Number chips   11
- Clock rate   3.4 MHz
- Cycle time   1.2 microseconds
- Memory   14K
- Power required   110 watts

Outputs
- Servo drivers   7
- Solenoids   3
- Discretes   3
- Digital   1

Logic
- 13 major paths
- 105 minor paths
- 79 schedules
- 500 constants

Physical
- 28 lb
- 801 cubic inches
- 200 lb/hr fuel cooled

LOGIC FEATURES

The figure on the next page shows the DEEC logic features. The basic nozzle area control modes include the idle nozzle area, set to a fixed value as a function of PLA, and the part power nozzle, set to a fixed value chosen to optimize thrust specific fuel consumption (TSFC).

At military power and above, at low Mach numbers, the nozzle controls engine pressure ratio (EPR) closed loop. At military power and above, at high Mach numbers (>1.4), the nozzle controls corrected fan rotor speed (N1C2) closed loop when fuel flow is controlling fan turbine inlet temperature (FTIT) and otherwise controls EPR closed loop. The basic EPR is a schedule of N1C2 biased by engine station 2 total pressure (PT2).

The gas generator fuel flow (WFGG) controls fan speed (N1) closed loop at all power settings, except when controlling to FTIT or running on FTIT limit.

Afterburner duct fuel flow (WFAD) is scheduled open loop to provide optimum fuel-air ratio for segments 3 and 5. The WFAD metering value position is controlled closed loop. Afterburner core fuel flow (WFAC) is scheduled open loop based on an optimum fuel-air ratio for segments 1, 2, and 4. The WFAC metering valve position is controlled closed loop. The sequencing valve position (SVP) regulates the fuel flow to the five segments of the augmentor.

Compressor inlet variable vanes (CIVVs) are scheduled open loop and are a function of corrected fan rotor speed (N1C2). Rear compressor variable vanes (RCVV) are scheduled open loop and are a function of corrected high compressor rotor speed (N2C25) and biased by engine station 2 total temperature (TT2). The start bleeds are controlled open loop and are a function of core rotor speed (N2) biased by TT2.

The DEEC performs the following functions:

(1) Detects engine stall by a certain rate of burner pressure (PB) decay and, as a function of PLA biased by PB, takes recovery action by cutting back fuel flow (WFGG) and opening the nozzle (AJ).

(2) Detects augmentor blowouts by one or more of the following indicators: a change in engine pressure ratio (EPR); a change in nozzle area; or loss of light off detector signal (LOD).

(3) Provides closed loop control of gas generator fuel flow (WFGG) during starts by trimming WFGG to obtain the desired high compressor rotor speed (see paper 8); and

(4) Provides fault detection and accommodation (FDA) by detecting 150 faults, some by use of range check and, if sensor is failed, will synthesize parameter (PB and FTIT) and detect open loop servovalve and actuator failures by voltage sum checks. Additional information on fault detection is in Paper 7.

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DEEC Logic Features

- Nozzle controls EPR

- Gas generator fuel flow controls N1

- Schedule augmentor fuel flow
  WFAD, WFAC, SVP

- Schedule variable geometry
  $CIVV = f(N1C2)$
  $RCVV = f(N2C25, TT2)$
  $SB = f(N2, TT2)$

- Detects stalls - recovery action
  $STLSIG = f(PLA, PB)$

- Detects A/B blowout
  $BLOSIG = f(\triangle EPR, LOD, \triangle AJ)$

- Closed loop start

- Provide failure detection and accommodation
  - 150 Faults
  - Range check all inputs
  - Parameter synthesis
  - Open loop servovalve or actuator

CLOSED-LOOP CONTROL MODES

The upper part of the figure shows the total airflow logic in which gas generator fuel flow (WFGG) is controlled to maintain the scheduled fan speed and hence, airflow. Proportional-plus-integral control is used to match the N1 request to the sensed N1. Limits of N2, FTIT, and PB are maintained. The airflow loop is used for all throttle settings.

Shown in the lower part of the figure is the engine pressure ratio (EPR) loop. The requested EPR is compared with the EPR, based on PT2 and PT6M, and, using proportional-plus-integral control, the nozzle is modulated to achieve the requested EPR. The EPR control loop is only active for intermediate power operation and augmentation. At lower settings, a scheduled nozzle area is used.

With the closed-loop airflow and EPR logic, the DEEC control is capable of automatically compensating for engine degradation. EPR is directly related to thrust, so the DEEC can maintain an engine at a desired thrust level. As the engine degrades, the FTIT required to achieve the scheduled EPR will increase until it reaches its limit. The DEEC will then operate the engine on the FTIT limit.
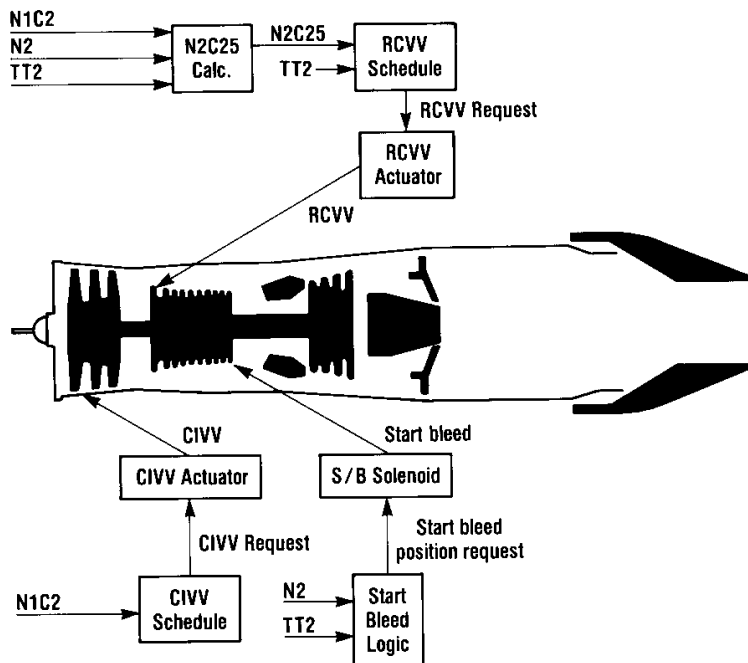
DEEC Basic Control Modes
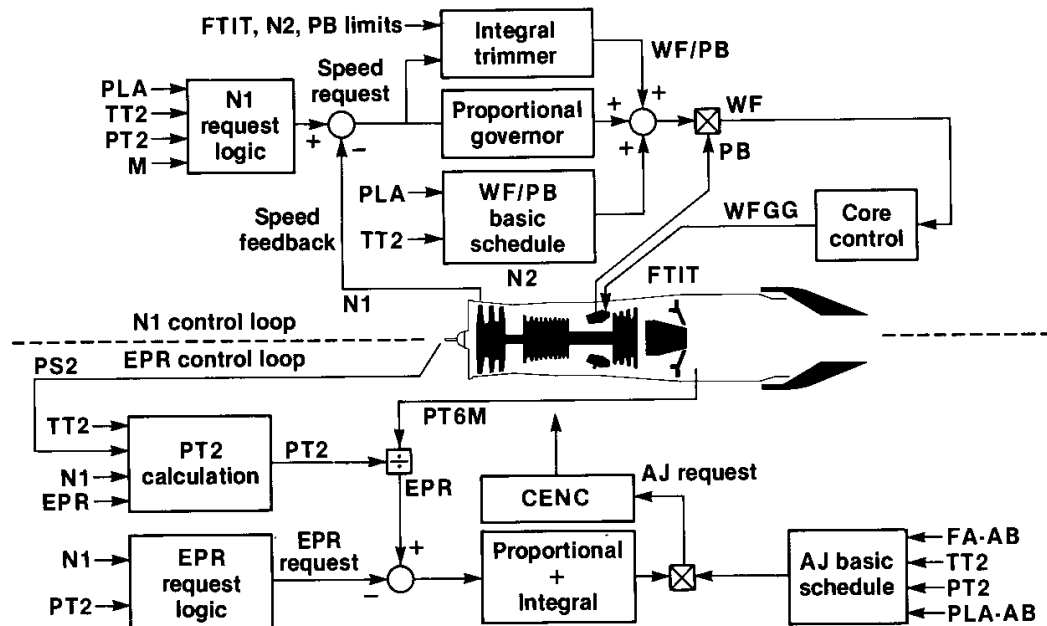
RCVV and CIVV are scheduled open loop as shown below. The resolvers in the actuators are used to generate feedback to position the vanes.

The start bleeds are scheduled and controlled open loop. The start bleed solenoid controls compressor discharge bleed air to close the bleeds.

Variable Geometry Logic

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FAULT DETECTION AND ACCOMMODATION

Power supply test - monitors internal power supply voltage and if a surge or drop is detected, will generate a power supply reset and transfer to BUC.

Cycle time test - monitors timely operation of program via software resets at specific intervals. Time out generates a reset signal for the processor and if repeated, transfers to BUC.

Clock loss test - monitors primary and secondary clocks for 1.7 MHz output. If output is not 1.7 MHz, it transfers to the secondary clock. If the secondary clock fails, it will transfer to BUC.

Amplifier drift test - monitors thermocouple amplifiers for voltage drift; failure of critical interface will transfer to BUC.

Feedback resolver test - monitors redundant resolver power supplies and tests resolver to digital converter.

Torque motor driver test - monitors "torque motor enable" and, "mode select" signals.

Open thermocouple test - monitors thermocouple amplifiers for off-scale voltage.

Torque motor "wrap around" test - monitors the two "sum" and four "difference" voltages of dual wound coils.

Processor test - checks for program "hangup" not detected in cycle test.

Scratch pad test - checks read and write integrity of each scratch pad location.

PROM check sum test - sum checks all read-only memories except vibrating cylinder sensor programmable read-only memories (PROMs).

Vibrating cylinder sensor checks - sum checks individual PROMs and range checks temperature input.

Parameter range check - checks for upper and lower limit.

Redundant parameter - checks for agreement within specified tolerances.

Open loop test - checks for nontracking actuator feedback versus command. Failure to correct "error" between request and feedback will generate a "loop shutdown".

More information on FDA is given in Paper 7.

Fault Detection & Accommodation

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DEEC

HARDWARE

- Power supply
- Cycle time
- Clock loss
- Amplifier drift
- Feedback resolver
- Torque motor driver

SOFTWARE

- Processor
- Scratch pad
- Prom check sum
- Vibrating cylinder prom
  - Check sum
  - Range check temp.

DEEC SYSTEM

- Open thermocouple
- Torque motor
  "Wrap Around"

- Parameter range check
- Redundant parameter
- Open loop